High Field HTS R&D Solenoid for Muon Collider

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***Abstract*—This paper presents the goal and status of the high field High Temperature Superconductor (HTS) solenoid program funded through a series of SBIRs. The target of this R&D program is to build HTS coils that are capable of producing fields greater than 20 T when tested alone and approaching 40 T when tested in a background field magnet. The solenoid will be made with second generation (2G) high engineering current density HTS tape. To date, 17 HTS pancake coils have been built and tested in the temperature range from 20 K to 80 K. Quench protection, high stresses and minimization of degradation of conductor are some of the major challenges associated with this program.**

***Index Terms*—High Temperature Superconductors, HTS, Muon Collider, Solenoid.**

I. INTRODUCTION

A muon collider [1] needs high field (up to ~50 T) solenoids for final ionization cooling [2, 3]. The use of high temperature superconductor is essential to obtain such high fields in this application. The R&D program presented here is funded through a series of SBIR (Small Business Innovative Research) awards to Particle Beam Lasers, Inc. (PBL), with Brookhaven National Laboratory (BNL) being a research partner to build HTS solenoids. BNL is also involved in a number of other HTS magnet R&D programs [4] and they all benefit from each other.

The first SBIR [5] is developing a ~10 T outer solenoid and the second SBIR [6] is developing a ~12 T insert solenoid. As a part of the second SBIR, the two solenoids will be nested, each in its own self-contained structure. This segmentation keeps the accumulated stress on the conductor below the maximum desired value. After completing the test of this ~22 T HTS solenoid at BNL, the plan is to take the magnet to the National High Magnetic Field Laboratory (NHMFL) in Florida to test it in the background field of a relatively long ~19 T large-bore resistive solenoid. That will test the HTS coils to fields approaching 40 T and will be an important technical milestone as it will determine if the conductor and coil can tolerate high stresses. However, as in previous such background field magnet tests [7], the field direction and the accumulation of stress due to Lorentz forces in it will be significantly different from a typical solenoid. In particular, the accumulated axial stress and direction of the field in the ends will be different as the outer coil in an actual solenoid cannot be as long as in NHMFL solenoid.

To extend fields above 30 T, one would need additional outer coils. A design has been examined where they were made with high current density Nb_3Sn Rutherford cable, as in accelerator magnets. However, that part of the program is yet to be funded and will not be discussed in this paper.

II. SOLENOID DESIGN

A. Design Considerations

Second generation (2G) HTS tape from SuperPower [8] is chosen for this application as it provides the highest engineering current density at very high fields (>20 T). SuperPower tape uses high strength Hastelloy substrate which is particularly suited for high field magnets where high stress from large Lorentz forces could limit the performance. To keep stress accumulation low, the magnet is segmented radially in two solenoids (inner and outer) with no stress transferred from inner to outer. This fits very well in the overall program as the two solenoids are made through separate SBIR grants. Once the high field testing of the solenoid is completed, it will be converted into a split pair solenoid under separate funding [9]. That solenoid will allow testing of samples (particularly irradiated HTS samples) as a function of field and field angle at various temperatures.

B. Magnetic Design

Main design parameters of the solenoid are given in Table I. The solenoid consists of two units (inner and outer) such that the inner solenoid fits well inside the outer while allowing maximum space for conductor. Moreover, the outer solenoid is designed such that it fits well inside the 19 T resistive solenoid at NHMFL. Both units are designed with ~4 mm wide and ~0.1 mm thick 2G HTS tape from SuperPower. The inner coil may further be divided in two radial segments to reduce the maximum stress.

The design fields for inner, outer and combined solenoid are optimistic targets. Based on the HTS solenoid tested earlier

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with similar conductor [7] and taking partial credit for improved performance, the expected performance of this solenoid is ~22 T. However, it should be pointed out that we are using an R&D conductor whose performance is still evolving. Moreover, the in-field performance is not well characterized and has been seen to vary significantly from production to production. In particular, the dependence of field as a function of angle plays an important role. Thus the field achieved in an individual and combined solenoid may turn out to be significantly different from those listed in Table I. It must be understood that this is an experimental R&D program to develop the technology rather than to design a magnet to reach the stated field target rigidly.

TABLE I MAIN DESIGN PARAMETERS

Target Design field (optimistic)	~22 T
Number of coils (radial segmentation)	2 self supporting
Stored Energy (both coils)	~110 kJ
Inductance (both in series)	4.6 H
Nominal Design Current	~220 A
Insulation (Kapton or stainless steel)	~0.025 mm
J_e (engineering current density in coil)	~390 A/mm^2
Conductor	2G ReBCO/YBCO
Width	~4 mm
Thickness	~0.1 mm
Stablizer	~0.04 mm Cu
Outer Solenoid Parameter	
Inner diameter	~100 mm
Outer diameter	~160 mm
Length	~128 mm
Number of turns per pancake	~240 (nominal)
Number of Pancakes	28 (14 double)
Total conductor used	2.8 km
Target field generated by itself	~10 T (@4.2 K)
Inner Solenoid Parameter	
Inner diameter	~25 mm
Outer diameter	~90 mm
Length	~64 mm
Number of turns per pancake	~260 (nominal)
Number of Pancakes	14 (7 double)
Total conductor used	0.7 km
Target field generated by itself	~12 T (@4.2 K)
External Radial support (overband)	Stainless steel tape

Fig. 1 shows the magnitude of the field in a 2-d axi-symmetric model, with field lines superimposed. The model shows only a symmetric half of the coil where the Y-axis is also the axis of the solenoid. In HTS magnets, the maximum current carried by the coil not only depends on the magnitude of the field but on the direction as well [10, 11]. In particular, the component perpendicular to the wide face has much lower field threshold. The perpendicular component can be significantly reduced from 6.22 T (see Fig. 2, on left) in the original design to 5.48 T (see Fig. 2, on right) by introducing only a 5 mm spacer before the last double pancake before the end. It produces only a small reduction in central field (from 22.22 T to 22.14 T).

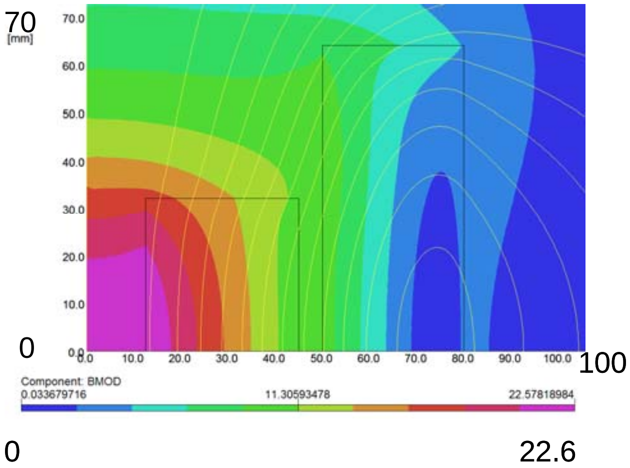

Fig. 1. Magnitude of the field (T) and field lines in an axi-symmetric model (length in mm).

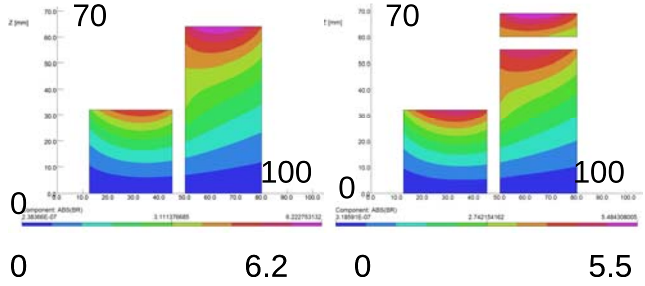

Fig. 2. Perpendicular component of the magnetic field (T) on the wide face of the tape (length in mm). A 5 mm gap before the last double pancake significantly reduces this component (see right).

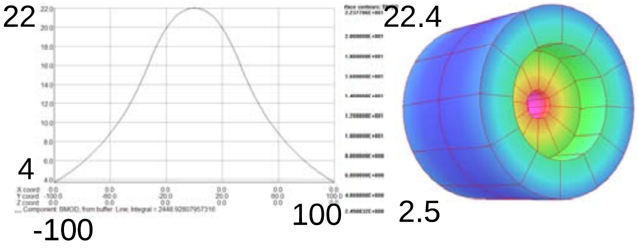

Fig. 3. Magnitude of the field (T) on the axis (see left) and on the surface of the coil in a ~22 T solenoid under construction.

Fig. 3 shows the magnitude of the field on the axis (right) and on the surface of the conductor in a 3-d model (left). Fig. 4 shows the parallel and perpendicular components of the field on the surface of the solenoid. The maximum parallel field on the surface of conductor in this model is 22.4 T and the perpendicular is ~6 T.

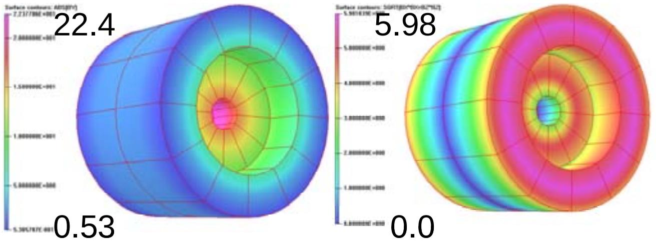

Fig. 4. Field parallel and perpendicular components of the field (T) to the wide face of the tape on the surface of the ~22 T solenoid.

C. *Mechanical Structure*

Mechanical structure plays a very important role in high field magnets. Not only should the external support structure around the coil be able to contain these large Lorentz forces, but also the stress within the coil should be kept below the value at which the conductor may become significantly degraded. As mentioned earlier, 2G HTS tape from SuperPower is based on Hastelloy and shows little degradation when the stress (average force divide by substrate area) is ~700 MPa at room temperature or ~1000 MPa at 77 K [8]. Similar data are not available (to same reliability) in other direction and an experimental program is being undertaken at BNL to determine those properties.

Stainless steel overband on the competed coil and winding tension during coil winding are used as the major components of the support structure. Once the coil is wound it is either impregnated or painted with epoxy.

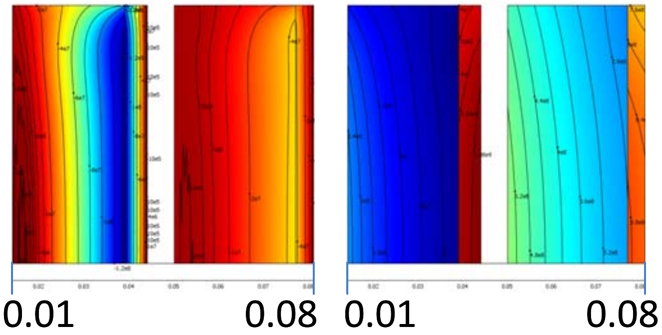

Fig. 5. σ_r [Pa] (left) and σ_φ [Pa] (right) stresses in magnets with 1 GPa pretension in inner-magnet banding. Coil radius is listed in meter.

Fig. 5. shows the radial and circumferential (hoop) stresses in the banded YBCO magnets with 1 GPa inner-magnet banding pre-stress to limit the radial tension to the ~5 MPa (700 psi). The modulus of the conductor is assumed to be 122.5 GPa, as reported by Superpower, Inc. [8]. The maximum radial compression is 137 MPa (20 ksi). The maximum circumferential tension is 260 MPa (38 ksi) in the inner magnet and 1.1 GPa (160 ksi) in its banding.

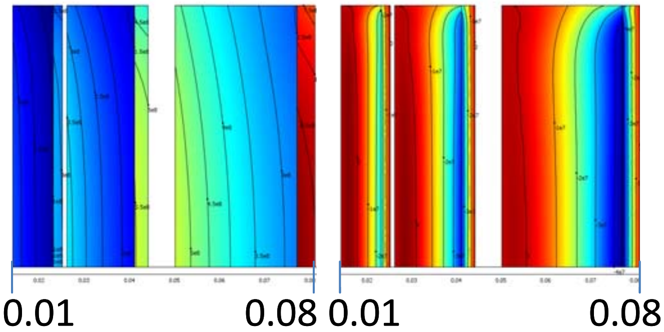

Fig. 6. σ_φ [Pa] (left) and σ_r [Pa] (right) stresses in magnet banded with $E_{band} = 3\ E_{cond.}$ MKS units are used with coil radius listed in meter.

Now we study the case when the inner magnet is radially partitioned into two subunits, each with its own banding. Fig. 6 plots the circumferential and radial stress in the magnet and banded with $E_{band} = 3\ E_{cond}$ with no pretension. $E_{band} = 3\ E_{cond}$ translates to Young's modulus of banding = three times that of the conductor winding pack. The maximum circumferential tension σ_φ is 548 MPa (79 ksi) in the outer unit and 889 MPa (129 ksi) in its banding. The respective values for the middle unit are 374 MPa (54 ksi) and 553 MPa (80 ksi) and, for the inner unit, 238 MPa (35 ksi) and 324 MPa (47 ksi). These values are comfortably below the 650-1,000 MPa that Superpower, Inc. says should be safe for their conductor. The maximum radial tension σ_r in each of the three magnets is, respectively, 1.2 MPa (180 psi), 2.8 MPa (400 psi) and 3.3 MPa (480 psi)—comfortable values for epoxy bonding.

III. QUENCH PROTECTION R&D

Protection of HTS magnets from thermal runaway (quench) remains a major challenge when the superconducting coil turns normal. Based on the large number of HTS coils built and tested at BNL, this has been observed to be a more severe problem in coils made with second generation (2G) HTS than those made with the first generation (1G) HTS. This may be partially due to lower amount of copper stabilizer in 2G as compared to the amount of silver stabilizer in 1G along with the higher current carrying capacity of 2G. As compared to conventional low temperature superconductor (LTS), the quench velocities in HTS are reported [12] to be significantly lower. The problem becomes more severe as field, stored energy and inductance become large.

The quench protection system under development will be made up of two sub-systems. The first will be a quench detector and the second is an energy extraction system. This quench protection system is qualitatively different than the protection systems used for LTS magnets because of the slow propagation velocity and low voltages associated with a quench. Quench protection is most complicated during the up and down ramps when the inductive voltage far exceeds the detection threshold for quenches.

Preliminary calculations show that it will take only 0.2 second to reach a temperature of 200 K from 4 K based on 40 micron thick copper in the YBCO tape used. Based on further analysis, the desired time constant to discharge this magnet should be 0.4 second or less. The anticipated peak discharge is few hundred volts through a dump resistor of few ohms. Increased amount of copper may help in magnet protection, however, at the expense of reduced current density.

The use of stainless steel insulating tape (instead of Kapton) in some coils adds to the complication. However, the measured resistance of stainless steel tape is found to be much larger than the few ohms in the energy extraction circuit, meaning only a small amount will be deposited in the coil. The benefit of using stainless steel is that it provides a parallel path during runaway and may help protect the coil.

IV. CONSTRUCTION AND TEST RESULTS

The outer coil consists of 28 pancake coils. So far 17 coils have been built and extensively tested in liquid nitrogen at ~77 K. In addition four of them have also been tested at lower temperature with helium gas. Results of these tests are discussed in detail by Shiroyanagi, et al. [13] in a separate paper in this conference. These results point to the number of challenges involved in dealing with the second generation superconductor that has a significantly smaller amount of stabilizer (40 micron). In the case of superconductor going normal, the current density in copper at 220 A will be ~1400 A/mm^2 (significantly more in a double pancake coil test when the fields are lower and hence currents can be higher).

V. FUTURE PLANS

The next major milestone in a few months is to build and test the outer solenoid with 14 pancake coils at ~4 K. This will be half the size since the complete solenoid needs 28 coils. Construction and test of the full solenoid will follow in about six months. This will complete the goals of the first SBIR [5].

The inner solenoid with 25 mm inner diameter and 14 pancake coils will be built and tested separately first in a temperature range of 4 K to 77 K. The inner and outer solenoid will be assembled together and tested in about nine months. The nested unit will then be prepared for test in the background field at NHMFL in Florida.

Together with this SBIR-supported work, generic R&D is underway at BNL to address the technical challenge of this and several other HTS magnet programs at BNL [4, 9, 14]. One important part of that work is developing a quench detection and energy extraction system that can be modified as needed to satisfy various HTS magnet programs. This experimental program involves building a series of small pancake coils with 25 mm inner radius and about 50 mm outer radius. Some of these coils will be bi-filar (see Fig. 7), some single and some double pancake. These coils will be used to test quench detection system and to measure the quench propagation velocities at various fields and temperatures.

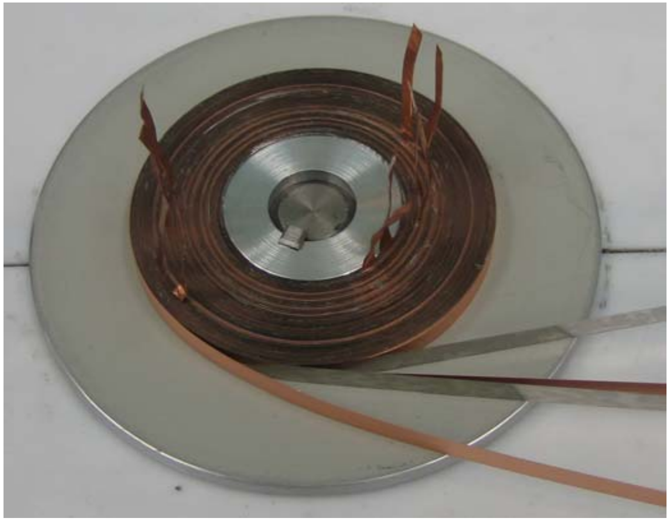

Fig. 7. Small test coil for future R&D. Above is a photo of a bi-filar coil that produces a zero net field and will be used in to study axial compression. Standard pancake coils have also been made for quench protection studies.

Currently there is limited information available on the stress tolerance of 2G HTS on the narrow side of the tape. This is critical to determine the limit of axial loading these coils can take in magnets due to Lorentz forces. Using a set-up developed for a previous program, a load will be applied on these small coils and in-situ performance will be measured as a function of load at liquid nitrogen temperature. Bi-filar coils will be used to minimize the influence of self-field.

VI. CONCLUSION

This paper has described an R&D program to develop key technology for high field HTS solenoid. The outcome of this R&D should be useful to other high field magnet programs as well. The goal of 22 T with limited funding is rather ambitious. Even though HTS coils have been tested at a much higher field in the background field from a long resistive solenoid, the differences in the direction of field and stress in the HTS coils makes this a challenging goal. In the absence of several key data and critical understanding in several areas, the program is being run as an experimental R&D program. Funding limitations of SBIR forces us to develop and test this new technology in the most cost-effective manner. Already significant understanding has been obtained from the 17 coils built and tested using 1.7 km of 2G HTS wire so far. When this experience is compared to ~50 coils made at BNL with the 1G HTS, it is observed that 2G HTS in the current form appears to be more prone to damage and degradation [9]. However, the use of 2G HTS in high field magnets is very attractive due to its ability to deliver large engineering current density at very high fields, its ability to handle large Lorentz forces and its ability to be wound into coils with small radii. Moreover, whereas the 2G HTS is being manufactured by two US vendors, 1G HTS is no longer made by any US vendor in significantly large quantities.

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